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VII. *An account of a series of experiments made with a view to the construction of an achromatic telescope with a fluid concave lens, instead of the usual lens of flint glass. In a letter addressed to DAVIES GILBERT, Esq. M.P. President of the Royal Society. By PETER BARLOW, Esq. F.R.S. &c.*

Read January 17, 1828.

YOU are aware that I have been for some time engaged in a set of experiments directed to the construction of achromatic fluid telescopes, and that I have succeeded in constructing, by the aid of Messrs. GILBERT, two instruments of that description, the one of 3 inches aperture and the other of 6 inches. You are aware also that it was my intention to have laid these before the members of the Board of Longitude; and if the construction had met with their approbation, I hoped they might have been disposed to have ordered a like instrument (but upon a scale much exceeding anything yet attempted), the construction of which it would have given me great pleasure to have superintended.

It is, however, doubtful whether I shall be able at present to pursue the experiments\*; and I wish therefore to place on record the progress I have made, the results which have been obtained, and the ultimate object I had in view; and I am in hopes this communication may not be thought undeserving a place in the Philosophical Transactions.

These experiments may perhaps date their origin from an attempt on the part of the opticians above referred to, to submit to actual practice the rules and principles laid down by Mr. HERSCHEL, in the Phil. Trans. for 1821, Art. XVII., for the construction of aplanatic object-glasses. These experiments led to others, which I have described in the Phil. Trans. for 1827, Art. XV. In following out the latter, I saw a strong practical instance of the great difficulty of obtaining flint glass of sufficient size and purity for astronomical telescopes; and this led me to consider the practicability of substituting a fluid for the

\* Since this paper was read, my letter has been presented to the Board of Longitude, and the experiments are in progress.

flint lens. Dr. BLAIR many years back had projected the construction of fluid object-glasses, and is said to have succeeded in making very perfect telescopes of that description. His view, however, in these constructions was not the same as mine; because with him it was still necessary to retain the flint lens; his only object being to destroy what has been named the secondary spectrum, due to a want of proportionality between the coloured spaces of the spectrums of flint and plate, or crown glass, as compared with their respective refractive indices; whereas my design was to dispense altogether with the flint glass, by substituting in its place a fluid medium of the requisite refractive and dispersive power.

A great number of fluids may be thus employed; and the first business was to determine amongst the many, that which seemed best suited for the purpose. With this view I undertook the examination of the properties of various oils, acids, &c. and was ultimately led to try the sulphuret of carbon, which at once appeared to claim a preference, and to possess nearly every requisite I could desire; having a refractive index about equal to that of the best flint glass, with a dispersive power more than double, perfectly colourless, beautifully transparent, and, although very expansible, possessing the same, or very nearly indeed the same, optical properties\*, when hermetically sealed, under all temperatures to which it is likely to be exposed for astronomical purposes,—unless indeed it should be found that direct observations on the solar disc in some extreme cases are inadmissible. Its high dispersive power also gives it an advantage which no glass ever made, or likely to be made, can possess; although the fixed nature of the latter material may probably always give it a preference in the construction of telescopes: and I wish clearly to be understood, not as proposing to supplant the use of flint glass in these instruments, but simply to supply its place by a valuable substitute, in cases where it cannot be obtained sufficiently large and pure; or where it can only be obtained at an expense which must always limit the possession of a powerful astronomical telescope, to a small number of individuals and to public bodies.

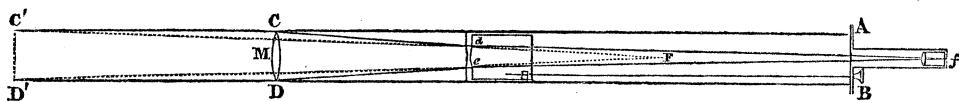
Having, as above stated, selected my fluid, my next object was to determine

\* It may be proper to state that, between the temperature of  $31^{\circ}$  in February and  $84^{\circ}$  in August, and again at  $31^{\circ}$  in December or November, I found no appreciable difference in the index or in the focal length of the telescope. The fluid has even been put in a state of ebullition by the application of red hot iron; and in a very few minutes has become transparent, and the focus remained either exactly or very nearly the same.

the best means of confining it, which after several trials was satisfactorily accomplished ; and I now at once attempted a telescope of 6 inches aperture and 7 feet in length : but after several unsuccessful experiments, arising from unforeseen difficulties, I laid it by, and undertook one of 3 inches aperture. I was here more fortunate, having with this instrument in its rude experimental form, without any adaptation or selection of glasses, separated a great number of double stars of that class which Sir W. HERSCHEL has pointed out as tests of a good  $3\frac{1}{2}$ -inch refractor. I can see with it the small star in Polaris with a power of 46 ; and with the higher powers several stars which are said to require a good telescope ; as for example, 70 p Ophiuchi, 39 Bootis, the quadruple star  $\epsilon$  Lyrae,  $\zeta$  Aquarii,  $\alpha$  Herculis, &c. Encouraged by my success on this instrument, I again attempted the 6-inch object-glass, with a different manner of adjusting and securing the lenses ; and the result of my endeavours I consider to be perfectly demonstrable of the practicability of the construction, allowance being made for the imperfections of a first attempt, at a novel construction, on a considerable scale, and which professes only to prove the applicability of the principle, and not the completion of the experiment. With this instrument the small star in Polaris is so distinct and brilliant with a power of 143, that its transit might be taken with the utmost certainty. The small stars in  $\alpha$  Lyrae, Aldebaran, Rigel,  $\epsilon$  Bootis, &c. are very distinctly exhibited ; amongst the larger close double stars, Castor and  $\gamma$  Leonis are well defined with a power of 300 ; and amongst the smaller double stars I may mention  $\omega$  Aurigæ, 52 Orionis,  $\zeta$  Orionis, and a variety of others of the same class. The belts and double ring of Saturn are well exhibited with a power of 150 ; and the belts and satellites of Jupiter are very tolerably defined with the same power, but will not bear a higher power than about 200, in his present situation, which is certainly not favourable : in both cases the discs of the planets are satisfactorily white, and belts and shadows well marked ; but in Jupiter, and perhaps in both, there is some uncorrected colour round the edge of the disc. Of this however I shall speak again after describing the principle of the construction.

In the usual construction of achromatic telescopes, the two or three lenses composing the object-glass, are brought into immediate contact ; and in the fluid telescope proposed by Dr. BLAIR the construction was the same, the fluid having been inclosed in the object-glass itself. Nor could any change in this

arrangement in either case be introduced with advantage, because the dispersive ratio between the glasses in the former instance, and between the glass and fluid in the latter, is too close to admit of bringing the concave correcting medium far enough back to be of any sensible advantage. The case, however, is very different with the sulphuret of carbon. The dispersive ratio here varies (according to the glass employed) between the limits 299 and 334 ; which circumstance has enabled me to place the fluid correcting lens at a distance from the plate lens equal to half its focal length ; and I might carry it still further back, and yet possess sufficient dispersive power to render the object-glass achromatic. Moreover, by this means the fluid lens, which is the most difficult part of the construction, is reduced to one-half, or to less than one-half, of the size of the plate lens ; consequently, to construct a telescope of ten or twelve inches aperture involves no greater difficulty in the manipulation, than in making a telescope of the usual description of five or six inches aperture, except in the simple plate lens itself : and, what will be thought perhaps of greater importance, a telescope of this kind of ten or twelve feet length will be equivalent in its focal power to one of sixteen or twenty feet. We may therefore, by this means, shorten the tube several feet, and yet possess a focal power more considerable than could be conveniently given to it on the usual principle of construction. This will be better understood from the annexed diagram.



In this figure, A, B, C, D represent the tube of the 6-inch telescope, C, D the plate object-glass, F the first focus of rays, *d e* the fluid concave lens, distant from the former 24 inches. The focal length M F being 48 inches, the diameter of the fluid lens is consequently as  $48 : 6 :: 24 : 3$  inches. The resulting compound focus is 62.5 inches : it is obvious, therefore, that the rays *d f*, *e f* arrive at the focus under the same convergency and with the same light, as if they proceeded from a lens of 6 inches diameter placed at a distance beyond the object glass C, D, (as C' D') determined by producing these rays till they meet the sides of the tube produced in C' D', viz. at 62.5 inches beyond the fluid lens. Hence, it is obvious, the rays will converge as they would do from an object-glass C' D' of the usual kind with a focus of 10 feet 5 inches.

We have thus, therefore, shortened the tube 38.5 inches, or have at least the advantage of a focus 38.5 inches longer than our tube ; and the same principle may be carried much further, so as to reduce the usual length of refracting telescopes nearly one-third without increasing the aberration in the first glass, beyond the least that can possibly belong to a telescope of the usual kind of the whole length. It should moreover be observed, that the adjustment for focus may be made either in the usual way, or by a slight movement of the fluid lens, as in the Gregorian reflector by means of the small speculum ; in the latter case the eye-piece is fixed, which may probably be convenient for astronomical purposes, in consequence of the great delicacy of the adjustment.

Besides the above advantages attending this principle of construction, I am willing to hope that another very important one (which I have not however been able at present practically to demonstrate) may still be effected ; namely, the reduction of what has been termed the secondary spectrum, either to zero or to a very inconsiderable amount. In order to examine the practicability of this object, let us first consider the two lenses in contact, and inquire into the conditions requisite for uniting the violet, the red, and the mean ray, which latter may be accounted that on the confine of the violet and red sides of the spectrum. Let the focal length of the mean ray in the plate lens be  $f$ , and the length of the focus beyond  $f$ , viz. the red side of the spectrum, be  $r$ , its whole focus being  $f + r$  ; let  $f'$ ,  $r'$  and of course  $f' + r'$  denote the same in the correcting fluid lens : then, in order that the red ray may coincide with the mean ray, we must have

$$\frac{1}{f} - \frac{1}{f'} = \frac{1}{f+r} - \frac{1}{f'+r'}$$

Now  $\frac{1}{f+r} = \frac{1}{f} - \frac{r}{f(f+r)}$

and  $\frac{1}{f'+r'} = \frac{1}{f'} - \frac{r'}{f'(f'+r')}$

therefore, when  $\frac{1}{f} - \frac{1}{f'} = \frac{1}{f+r} - \frac{1}{f'+r'}$

we must have  $\frac{r}{f(f+r)} = \frac{r'}{f'(f'+r')}$

and therefore,  $f : f' : : \frac{r}{f-r} : \frac{r'}{f'+r'}$

That is, the mean focal lengths must be to each other as the red part of the

focus divided by the whole focal length of the red ray, or, as the dispersive powers for this side of the spectrum, in each lens.

In the same way, if we denote by  $v$  and  $v'$  the length of the violet part of each focus ; then to have the violet and the mean ray coincide, we must have

$$\frac{1}{f} - \frac{1}{f'} = \frac{1}{f-v} - \frac{1}{f'-v},$$

and as before, we shall find that this can only take place when

$$\frac{v}{f(f-v)} = \frac{v'}{f'(f'-v')} : \text{ or when } f : f' :: \frac{v}{f-v} : \frac{v'}{f'-v'};$$

Hence, in order to unite these three colours, the conditions must be that

$$\frac{r}{f+r} : \frac{v}{f-v} :: \frac{r'}{f'+r'} : \frac{v'}{f'-v'}.$$

But as  $f, r$  and  $v$ , in one case, and  $f', r'$  and  $v'$ , in the other, are dependent and proportional in each respective focus, if these proportions do not arise from the natural properties of the two media, they cannot be produced by art, while the lenses are in contact ; but in any case where the violet side of the correcting or concave lens exceeds that of the red in a greater proportion than the violet exceeds the red in the convex lens, and if the dispersive ratio be so great as to admit of the lenses being sufficiently opened from each other, then such a distance may be found as shall produce the above proportion ; and hence unite these three rays in one common focus, or at least approximate towards this result.

Let the distance of the lenses be  $d$ , and let the plate focus remain as before  $f$ , then the negative focus must be reduced till  $\frac{(f-d)^2}{ff'} = \text{dispersion}^*$ .

Conceive this length to be found, which may still be denoted by  $f''$ , and  $r'$  and  $v'$  may also denote the same as before, the ratio  $\frac{r'}{f'-r'}$  to  $\frac{v'}{f'-v'}$  will likewise still remain the same.

But the coloured focus of the plate lens remaining the same as before, while the mean focus is changed from  $f$  to  $f-d$  ; we must now, in order to unite the three rays, have

$$\frac{r}{f-d+r} : \frac{v}{f-d-v} :: \frac{r'}{f'+r'} : \frac{v'}{f'-v'}$$

The two latter terms remaining in the same ratio, while the two former may be varied at pleasure by changing the value of  $d$  ; which will have no effect on the ratio of the latter terms, although the actual value of  $f', r'$  and  $v'$ , must necessarily vary for every change in the value of  $d$ .

\* Phil. Trans. 1827, Art. XV.

Let the constant ratio of the latter terms be  $m : n$ ; then we have to find  $d$ , such that,

$$\frac{r}{f-d+r} : \frac{v}{f-v-v} :: m : n; \text{ or, } \frac{nr}{f-d+r} = \frac{mv}{f-d-v};$$

which reduced, gives  $d = \frac{mvf + mvr - nr f + nr v}{mv - nr}$ .

If now  $a'$ ,  $a''$ ,  $a'''$  be taken to denote the refractive indices of the red, green, and violet ray in the front lens, we shall find  $f$ ,  $r$  and  $v$ , to be to each other as 1,  $\frac{a''-a'}{a'}$ , and  $\frac{a'''-a''}{a'''}$ ; and substituting these proportional values for the above letters, our expression becomes

$$d = f a'' \left\{ \frac{m(a'''-a'')-n(a''-a')}{m a' (a'''-a'')-n a''' (a''-a')} \right\}$$

In like manner, if  $\alpha'$ ,  $\alpha''$ ,  $\alpha'''$  be taken to denote the refractive indices of the red, green, and violet ray in the correcting lens, then we shall find

$$\frac{r'}{f'+r'} : \frac{v'}{f'-v'} :: m : n :: \alpha''-\alpha' : \alpha'''-\alpha''$$

Which latter may therefore be substituted for  $m$  and  $n$ .

The formula then becomes

$$d = f a'' \left\{ \frac{(\alpha''-\alpha')(a'''-a'')-(\alpha'''-\alpha'')(a''-\alpha')}{(\alpha''-\alpha')(a'''-a'') a' - (\alpha'''-\alpha'')(a''-\alpha') a''' } \right\}$$

an expression for the distance in terms of the indices and focus only.

In plate glass, according to FRAUNHOFER,  $a' = .515$ ,  $a'' = .525$ , and  $a''' = .535$ . Which values being substituted, give

$$d = f \left\{ \frac{(\alpha''-\alpha')-(\alpha'''-\alpha'')}{.981(\alpha''-\alpha')-1.019(\alpha'''-\alpha'')} \right\}$$

In flint glass, from the same authority,  $\alpha' = .602$ ,  $\alpha'' = .620$ ,  $\alpha''' = .640$ . Which numbers being substituted, give  $d = .734 f$ . An impracticable distance in this case, because the dispersive power of flint glass is not great enough to correct the plate lens when so far removed.

If these indices had been .602, .621, and .640, then we should find  $d = 0$ , or the lenses ought then to be in contact. A change therefore of .001 in the index of the green ray, changes the distances of the lenses from nothing to nearly three-fourths of the whole focus of the plate; consequently, the determination of the proper distance to combine the three colours, when the media are such as to admit of it, depends upon the most delicate determination of the indices of the red, green, and violet rays; but these being so determined, and the di-

spersive power of the medium being great enough, the most complete union may be effected.

Whether the sulphuret of carbon fall within this limit or not, I am not at present able to say. I have attempted to find the indices of the different colours by means of a prism ; but it is extremely difficult to determine the limits of the different shades, and perhaps after all the best way is by actual experiment on the telescope itself. Fearful in the beginning of advancing too far in opening the lenses, the first experiment was made with the fluid at a very inconsiderable distance behind the plate, and the quantity of uncorrected colour was very great. I next tried a distance of 18 inches, and the uncorrected colour was considerably less than before, but still too great. With this distance the experiment was witnessed by Captain KATER. I next opened the lenses 24 inches, and at this distance the experiment was witnessed by Professor AIRY, who still detected some uncorrected colour, which, however, is not sensible to my eye till the telescope is applied with a high power to Jupiter, Venus, or some bright star ; neither was this defect felt in any sensible degree by Mr. SOUTH or Captain BEAUFORT, who were also present.

From the gradual diminution of the outstanding purple by opening the lenses from contact to 24 inches, I suspect with a distance of 32 inches, (which is perhaps the most I can venture upon with a focus of 48 inches for my plate,) that the red would be outstanding, and if so the proper point must be between these limits.

This, however, remains to be verified by experiment ; should it be effected, we may enumerate the advantages of this telescope as follow :

1. It renders us independent of flint glass.
2. It enables us to increase the aperture of the telescope to a very considerable extent.
3. It gives us all the light, field, and focal power of a telescope of one and a half times at least, probably of twice the length of the tube.
4. It is presumed that further experiments may enable us to find such a distance for the lenses as shall reduce what has been termed the secondary spectrum, (inseparable from the usual construction,) either to zero or to an inconsiderable amount.